Water Quality Impact Assessment of Large-scale Bioenergy Crop Expansion

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Introduction

- Fossil fuels account for about 80 percent of global energy supply, and will be exhausted in a matter of decades at current consumption rates (Goldemberg, 2007).
- The instability of the global energy sector has led to recent increases in the demand for alternatives, most notably bioenergy.
- The sustainability and environmental implications of bioenergy production are not well understood (Carroll and Somerville, 2009).

BIOENERGY – Associated Benefits

- Greenhouse gas mitigation through carbon sequestration
- Reduce dependency on foreign countries, typically having weak political stature
- Cutting consumer cost and create jobs

BIOENERGY – Associated Problems

- More freshwater for irrigation is required, even though farming accounts for 80 percent of all water consumed in the United States
- Non-Point Source pollution will likely increase due to more agricultural inputs

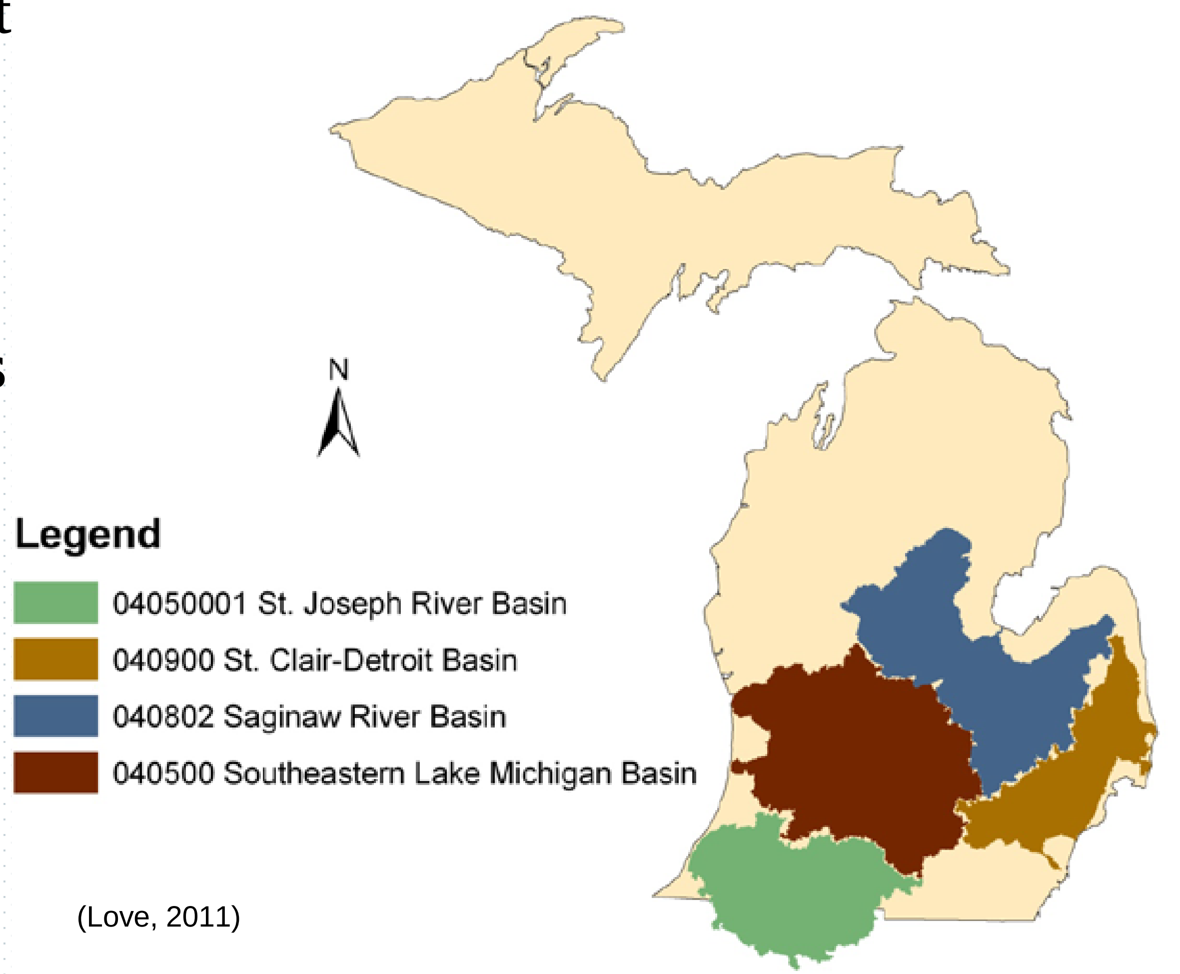
Research Objectives

- Determine impacts of bioenergy on water quality:
  - Sediment
  - Total Nitrogen
  - Total Phosphorus

Methodology

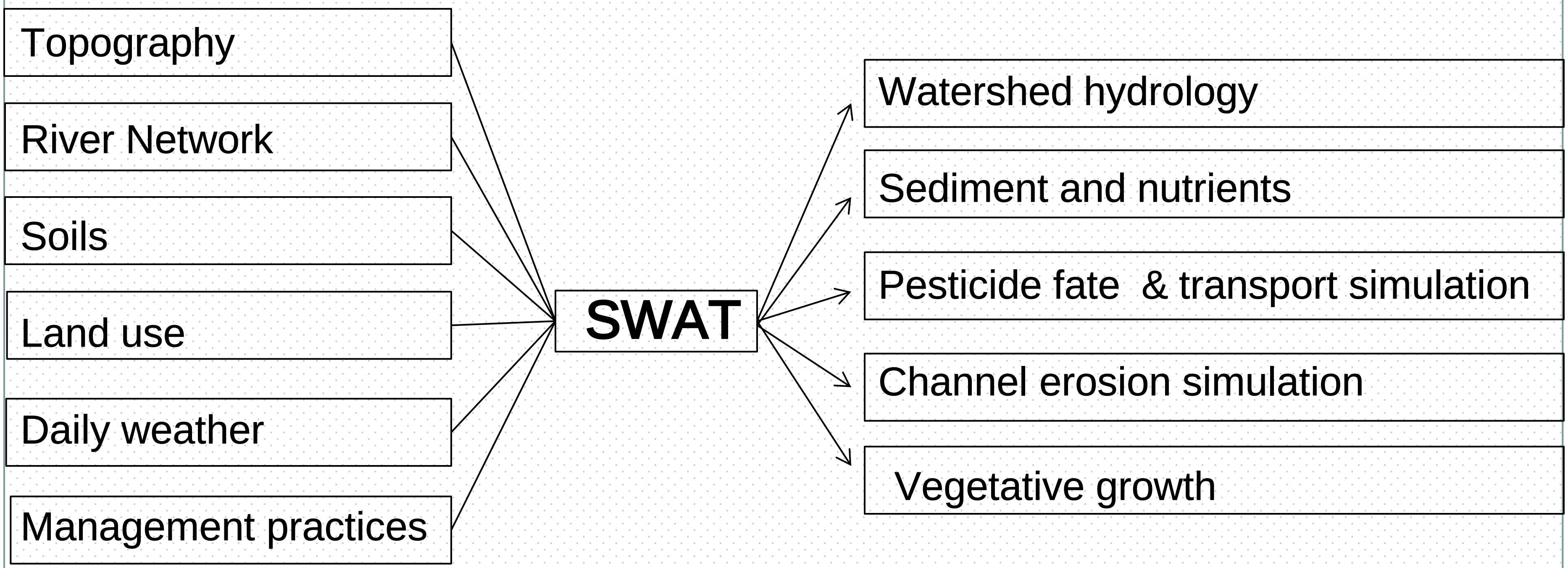
Study Area

- Larger scale impact assessment
- 53,358 km^2
- 4 Large watersheds
- 879 Subbasins
- 5970 km streams



Watershed Models

– **Soil and Water Assessment Tool (SWAT)**



Model Setup

- 19 Year period of study (1990-2008)
- Model Input
  - State Soil Geographic Database (STATSGO)
  - Elevation from USGS Digital Elevation Model
  - Stream network delineated based on NHD
  - Land cover based on 2008 Cropland Data Layer
  - Daily weather data from National Climatic Data Center
    - 195 Precipitation Stations
    - 158 Temperature Stations

Crop Rotations & Management Operations

- 15 Bioenergy crop rotations
- Accurately reproduce the local agricultural practices
  - For example, first year of corn-soybean-canola rotation

Date	Practice	SWAT Practice	Amount/ha
May-1	Soil Finish		
May-4	Nitrogen Application	Urea	194 kg
May-4	Soil Finish	Field Cultivator Ge15ft	
May-5	Phosphorus Application	Elemental Phosphorus	59.5 kg
May-5	Plant Corn Seed	Plant/Begin Growing Season	
May-5	Bicep II Magnum ® (PRE)	Atrazine	1.39 kg
May-5	Bicep II Magnum ® (PRE)	Metolachlor	1 kg
Nov-1	Combine Harvest Corn Grain	Harvest and Kill	
Nov-15	Fall Chisel	Coulter-chisel Plow	

(Love, 2011)

Landuse Scenarios

Four landuse scenarios were developed:

– Scenario 1: Row Crops (e.g. grains, hays, seeds)

– Scenario 2: Other Crops (e.g. sugarbeets, potatoes)

– Scenario 3: Marginal Land (e.g. fallow cropland, pasture, wasteland)

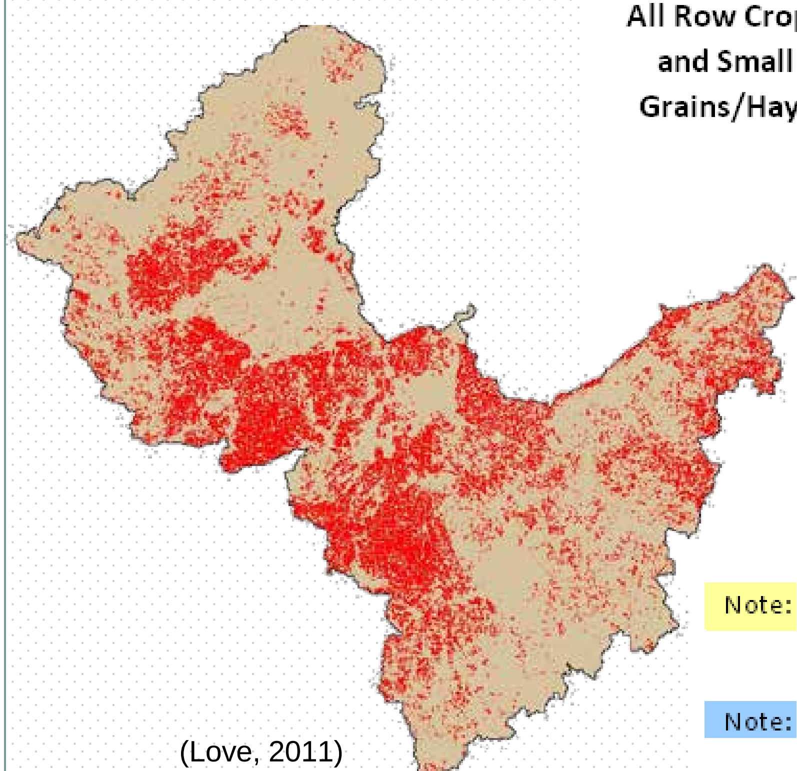
– Scenario 4: All Tillable Land

Landuse Scenarios

– Each scenario was subject to a series of reviews in order to provide the most realistic rotations for the region of study :

- climate
- preexisting harvesting equipment
- expected productivity of each crop on the given soil types,
- willingness of farmers to alter preexisting management practices to accommodate new cropping systems.

Scenario 1: Row Crops



(Love, 2011)

All Row Crops and Small Grains/Hays

Bioenergy Crops

- Barley
- Cassava
- Corn
- Potato
- Canola
- Rice
- Rye
- Sorghum
- Soybean
- Sugarbeet
- Sugar Cane
- Wheat
- Jatropha
- Miscanthus
- Switchgrass
- Corn Stover
- Native Grasses

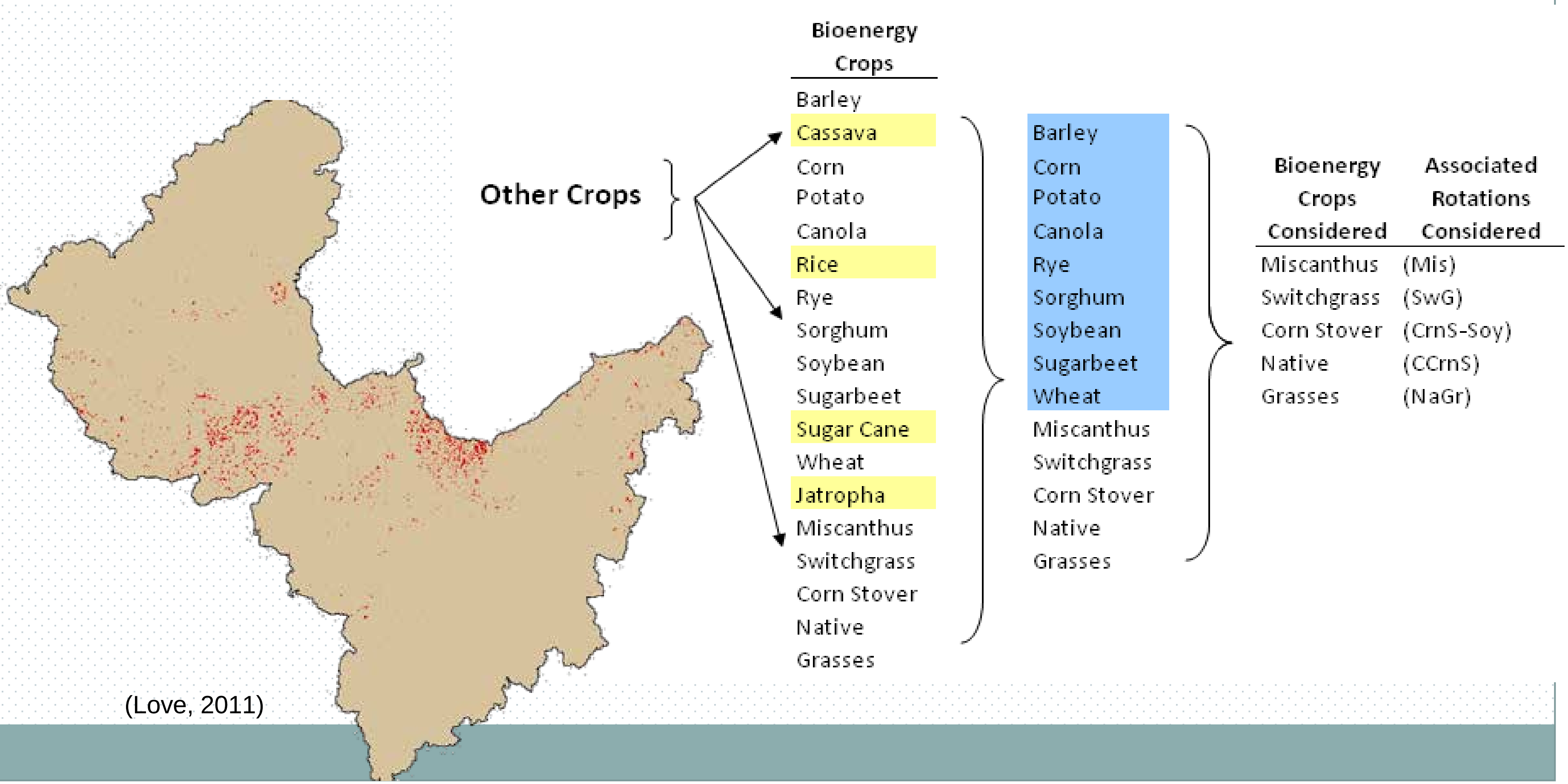
- Barley
- Corn
- Potato
- Canola
- Rye
- Sorghum
- Soybean
- Sugarbeet
- Wheat
- Miscanthus
- Switchgrass
- Corn Stover
- Native Grasses

Bioenergy Crops Considered	Associated Rotations Considered
Corn	(Crn-Soy-Can)
Canola	(Crn-Soy-Rye)
Rye	(Crn-Soy)
Sorghum	(CrnS-Soy)
Soybean	(CCan)
Miscanthus	(CCrn)
Corn Stover	(CCrnS)
Switchgrass	(CRye)
Native Grasses	(Srg-Soy)
	(CSrg)
	(Csoy)
	(Mis)
	(SwG)
	(NaGr)

Note: Cells with yellow fill denote crops determined to be inapplicable to the scenario. Due to the regions physical attributes, climate, and preexisting harvesting equipment, these crops would be unlikelt to establish significant yields.

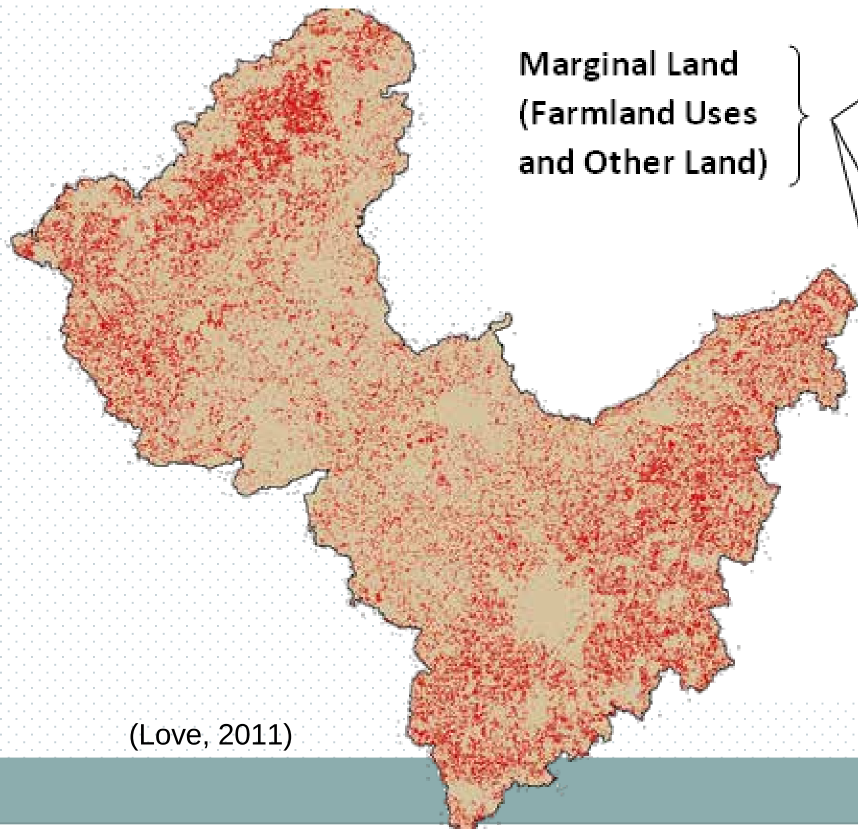
Note: Cells with blue fill denote crops that would further be defined as "poor suitability" based on excessive capital cost for equipment, low productivity on many soil types present in the watershed, and suitability for farmers to alter preexisting management practices to accommodate new cropping systems.

Scenario 2: Non-Row Crops



(Love, 2011)

Scenario 3: Marginal Land



Marginal Land (Farmland Uses and Other Land)

Bioenergy Crops

- Barley
- Cassava
- Corn
- Potato
- Canola
- Rice
- Rye
- Sorghum
- Soybean
- Sugarbeet
- Sugar Cane
- Wheat
- Jatropha
- Miscanthus
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- Barley
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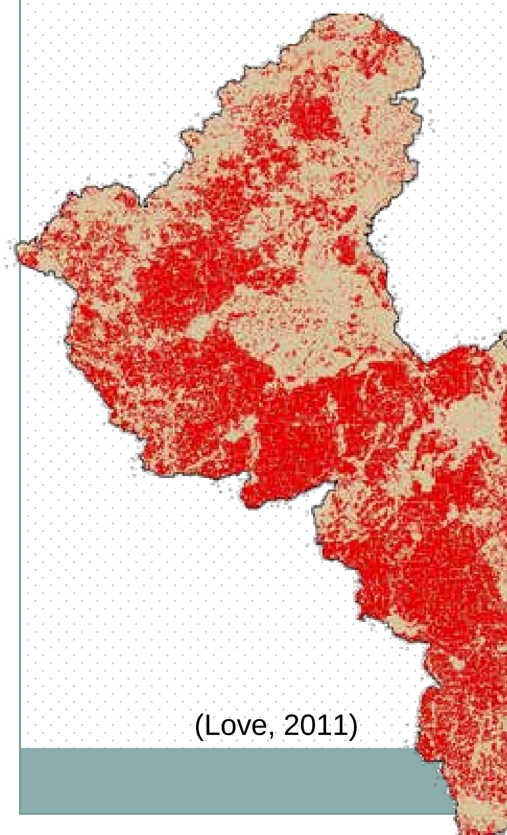
Bioenergy Crops Considered	Associated Rotations Considered
Corn	(Crn-Soy-Can)
Canola	(Crn-Soy-Rye)
Rye	(CCrn)
Switchgrass	(CCan)
Miscanthus	(CRye)
Native	(Mis)
Grasses	(SwG)
	(NaGr)

(Love, 2011)

Scenario 4: All Agricultural Land



(Love, 2011)

Row Crops, Small Grains/Hays, Other Crops and Marginal Land

Bioenergy Crops

- Cassava
- Corn
- Potato
- Canola
- Rice
- Rye
- Sorghum
- Soybean
- Sugarbeet
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- Wheat
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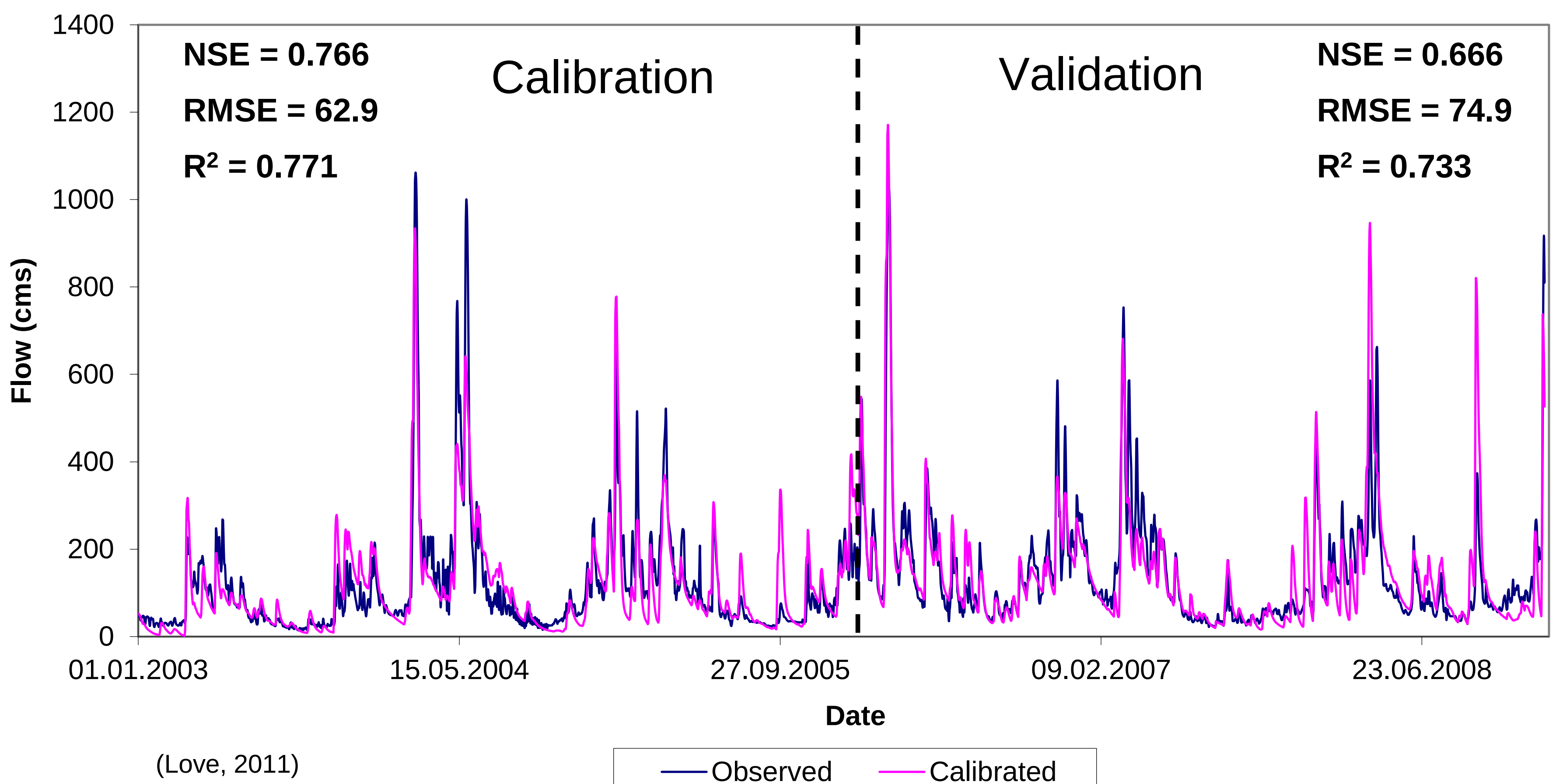
Switchgrass	(CCan)
Corn Stover	(CRye)
Native Grasses	(CSrg)
	(CSoy)
	(Mis)
	(SwG)
	(NaGr)

Calibration/Validation

- Calibration performed on daily basis
  - Flow
  - Sediment
  - Nitrogen
  - Phosphorus
- Calibration criteria
  - Nash-Sutcliffe efficiency (NSE >0.5)
  - Coefficient of determination (R^2 >0.5)
  - Root mean-squared error (RMSE)

Calibration/Validation Hydrograph



(Love, 2011)

Results and Discussion

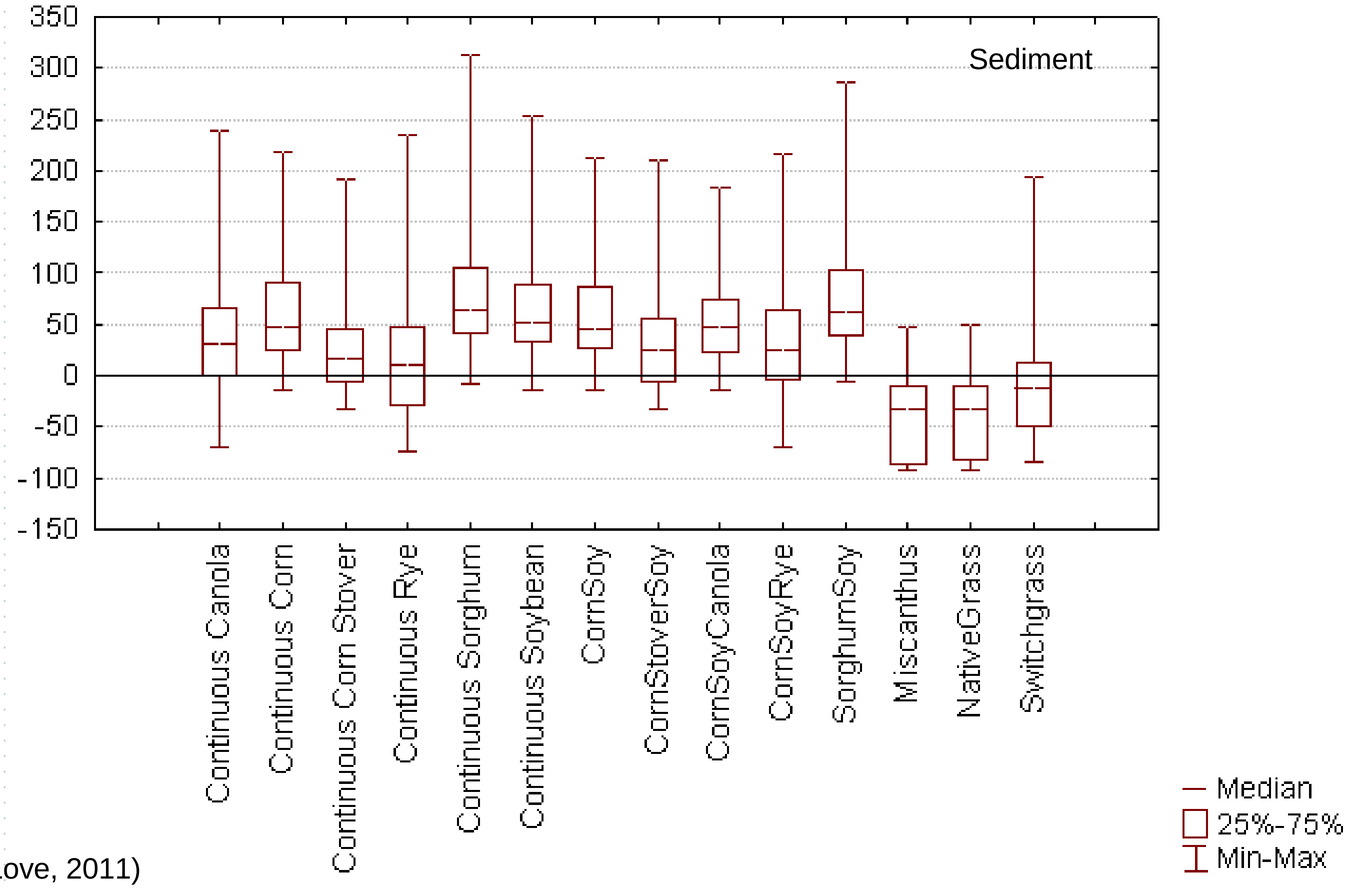
Specific Goals

- Goal 1. Basin-wide impact of bioenergy cropping rotations
- Goal 2. Basin-level priority areas for targeting conservation efforts
- Goal 3. Suitability of bioenergy cropping rotations on different scenarios
- Goal 4. Statistical significance of bioenergy cropping rotations changes from base

Goal 1

- Basin-wide impact of bioenergy cropping rotations
  - Average annual sediment, total nitrogen, and total phosphorus loads was obtained for each watershed at the outlet for the study period

19-year annual average basin-wide pollution load at the watershed outlet



(Love, 2011)

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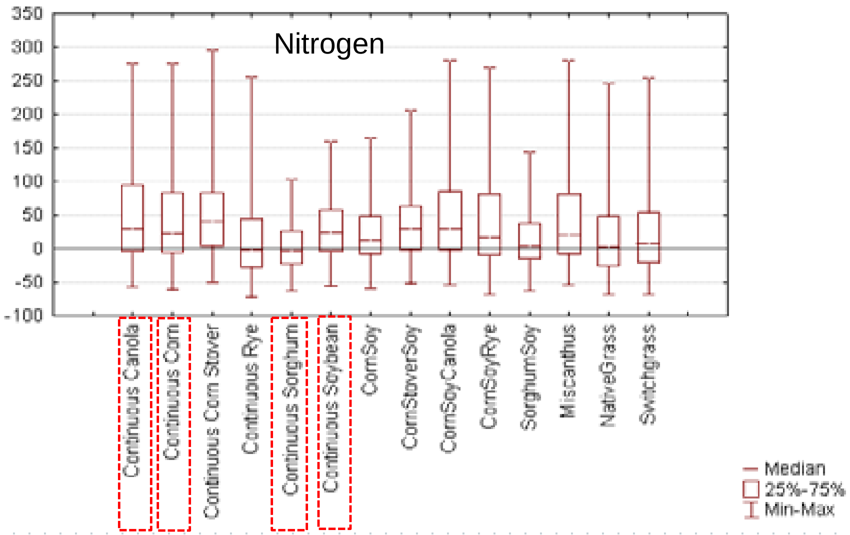
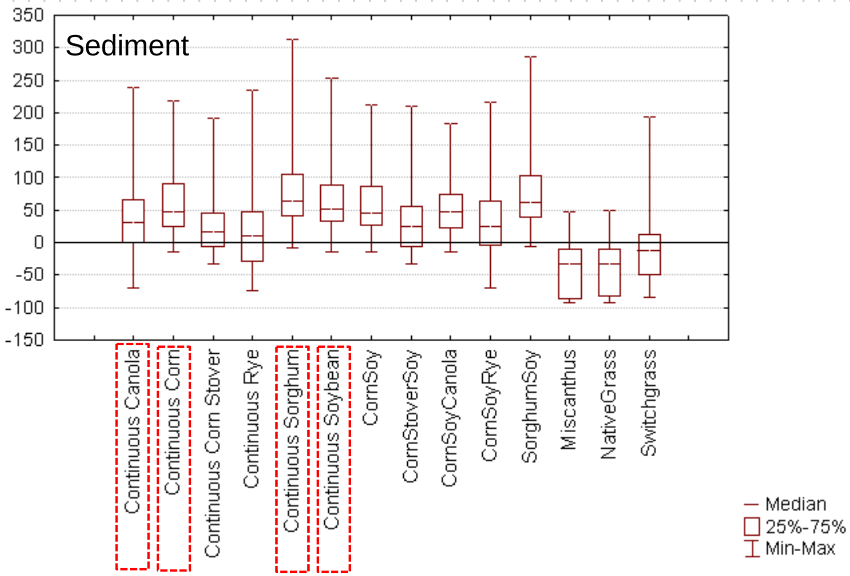
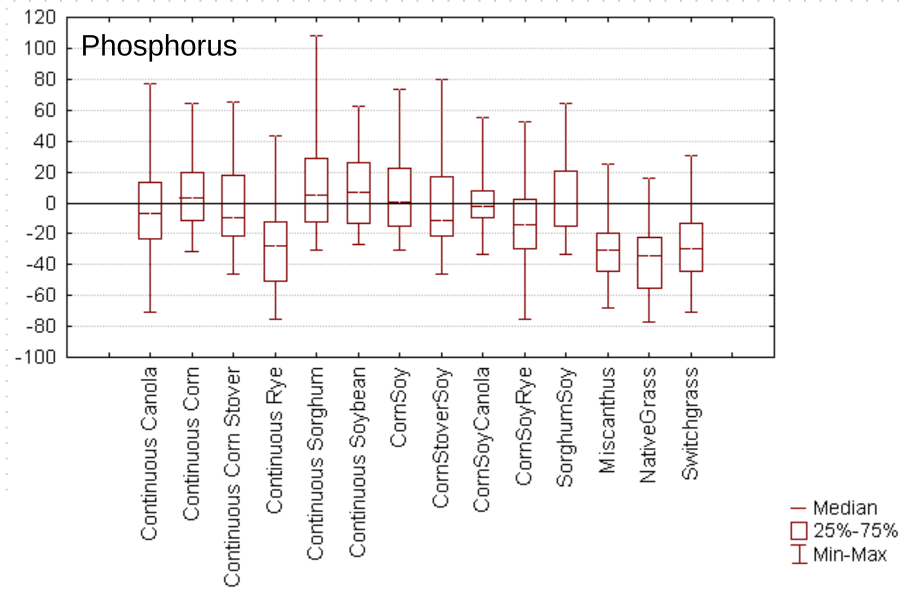


- Traditional, intensive crops such as corn, sorghum, canola and soybean experience increases in sediment and nitrogen load

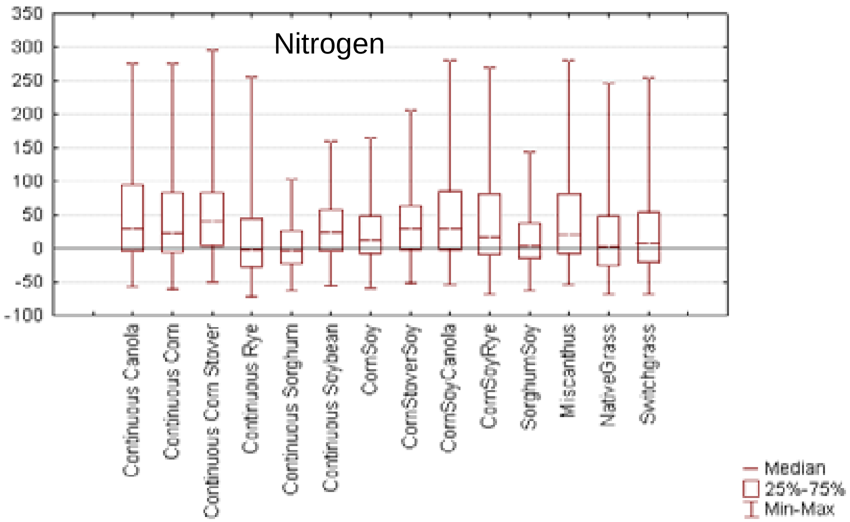
(Love, 2011)





19-year annual average basin-wide pollution load at the watershed outlet

- In certain cases has the potential to reduce phosphorus loads



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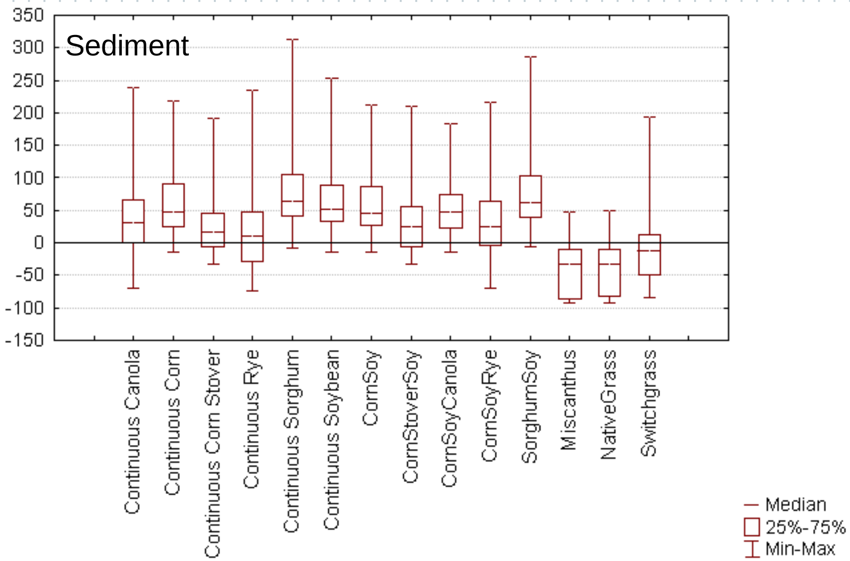

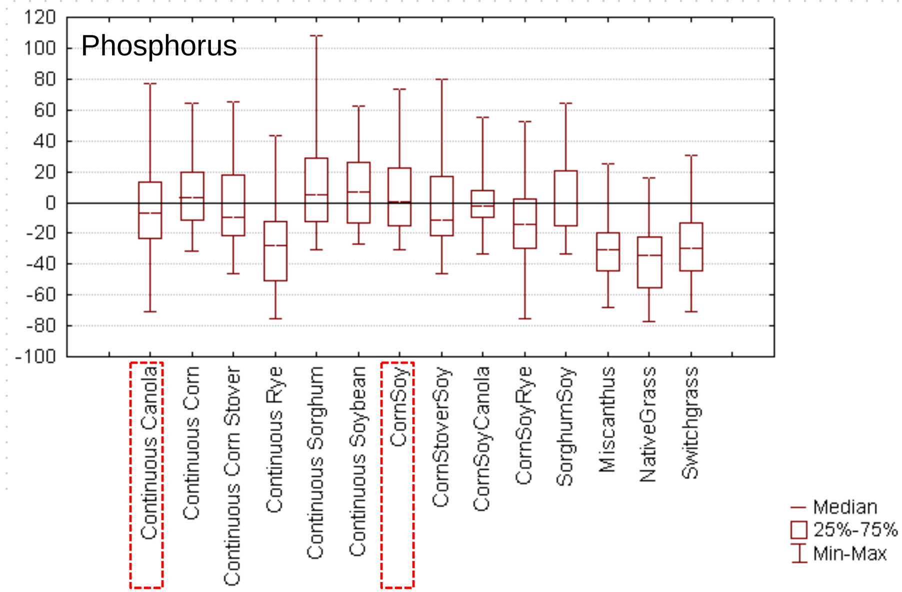

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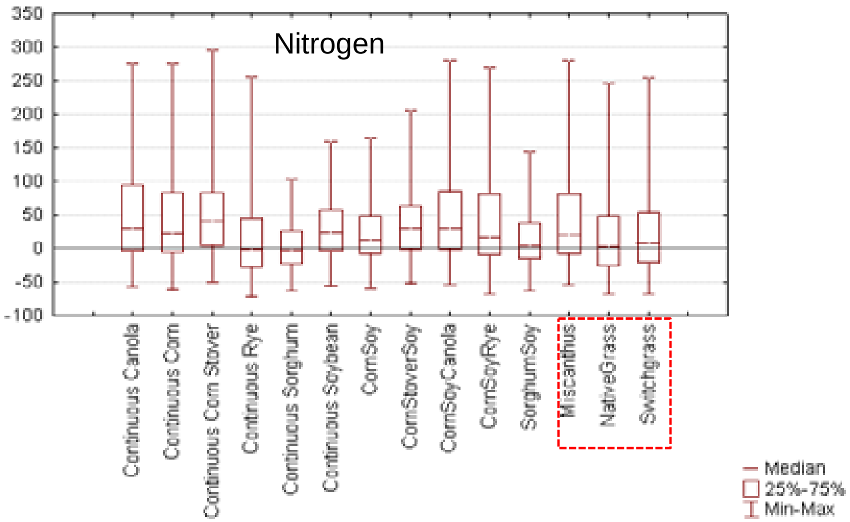
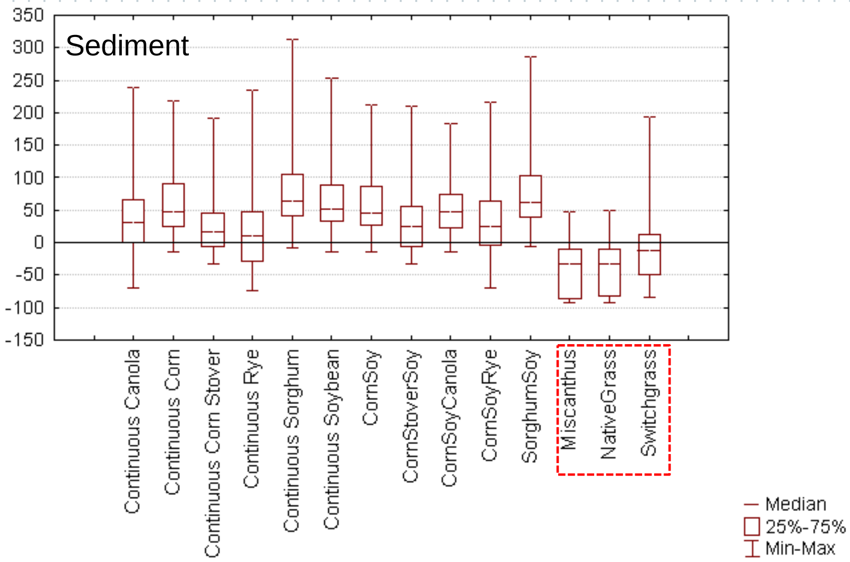
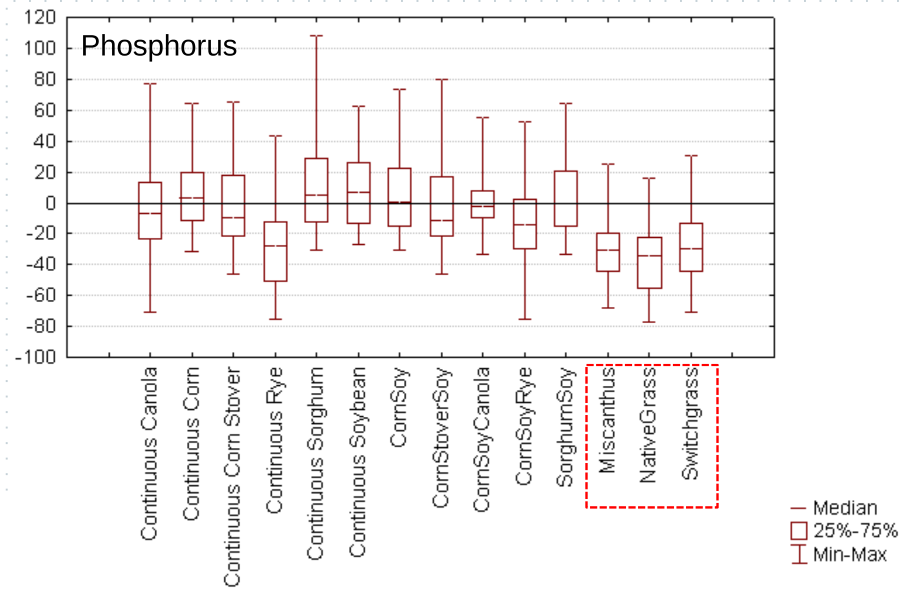


- the perennial grass species (miscanthus, native grasses, and switchgrass) extensively mitigate sediment and phosphorus, yet have the potential to increase nitrogen slightly.

(Love, 2011)





Summary Goal 1

– Perennial grass species are most suitable for large-scale implementation in this study areas.

– Traditional intensive row crops should be implemented with caution on such a broad scale.

Goal 2

– Basin-level priority areas for targeting conservation efforts

- Three classes (low, medium, and high) of priority concerns were formed by dividing the study area based on what was essentially a quantile classification for each constituent.

- Scenario 4 of the landuse conversion represents the most extreme scenario, therefore; the impacts of landuse conversion on both priority concerns areas and reaches were evaluated by comparing Base Scenario and Scenario 4

Length of priority reach change from the Base Scenario (km)

	Sediment			Nitrogen			Phosphorus		
	Low	Medium	High	Low	Medium	High	Low	Medium	High
Continuous Canola	-1944	998	946	-2437	-810	3247	-1638	981	658
	-32.56	16.72	15.84	-40.82	-13.56	54.38	-27.44	16.43	11.02
Continuous Corn	-2438	836	1602	-2321	-263	2584	-1820	894	926
	-40.83	14.00	26.83	-38.88	-4.40	43.28	-30.48	14.97	15.52
Continuous Corn stover	-2571	749	1822	-2472	-1584	4055	-2323	801	1521
	-43.06	12.54	30.53	-41.40	-26.52	67.93	-38.90	13.42	25.48
Continuous Rye	-2281	1218	1062	-2120	259	1861	111	333	-443
	-38.20	20.41	17.79	-35.52	4.34	31.18	1.85	5.57	-7.42
Continuous Sorghum	-2628	291	2338	-2242	-102	2343	-2199	706	1493
	-44.02	4.87	39.15	-37.55	-1.70	39.25	-36.83	11.82	25.00
Continuous Soybean	-2588	425	2162	-2418	-936	3354	-2209	780	1429
	-43.34	7.13	36.22	-40.50	-15.67	56.17	-37.00	13.06	23.94
Corn Soy	-2588	556	2031	-2389	-732	3121	-2155	755	1400
	-43.34	9.32	34.03	-40.01	-12.26	52.28	-36.09	12.65	23.44
Corn Soy Rye	-2399	1010	1389	-2373	-366	2738	-1116	964	152
	-40.18	16.92	23.26	-39.74	-6.12	45.87	-18.69	16.15	2.55
Corn stover Soy	-2588	602	1985	-2457	-966	3422	-2266	774	1492
	-43.34	10.08	33.26	-41.15	-16.18	57.33	-37.95	12.96	25.00
Sorghum Soy	-2623	318	2306	-2343	-525	2868	-2080	852	1227
	32.40	-10.58	-21.82	-38.11	-5.74	43.85	11.13	3.75	-14.88
Miscanthus	1934	-632	-1303	-2275	-342	2618	665	224	-889
	30.93	-10.40	-20.53	-22.20	15.10	7.10	32.09	-9.00	-23.09
Native Grass	1846	-621	-1226	-1326	901	424	1916	-537	-1379
	-43.94	5.32	38.62	-39.25	-8.79	48.04	-34.84	14.28	20.56
Switchgrass	-1034	915	118	-2030	264	1766	724	-138	-586
	-17.31	15.33	1.98	-34.00	4.43	29.57	12.12	-2.31	-9.81

(Love, 2011)

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(Love, 2011)

Priority Streams for Base, Continuous Corn, and Switchgrass Scenarios

Base | Corn | Switchgrass

Sediment

Nitrogen

Phosphorus

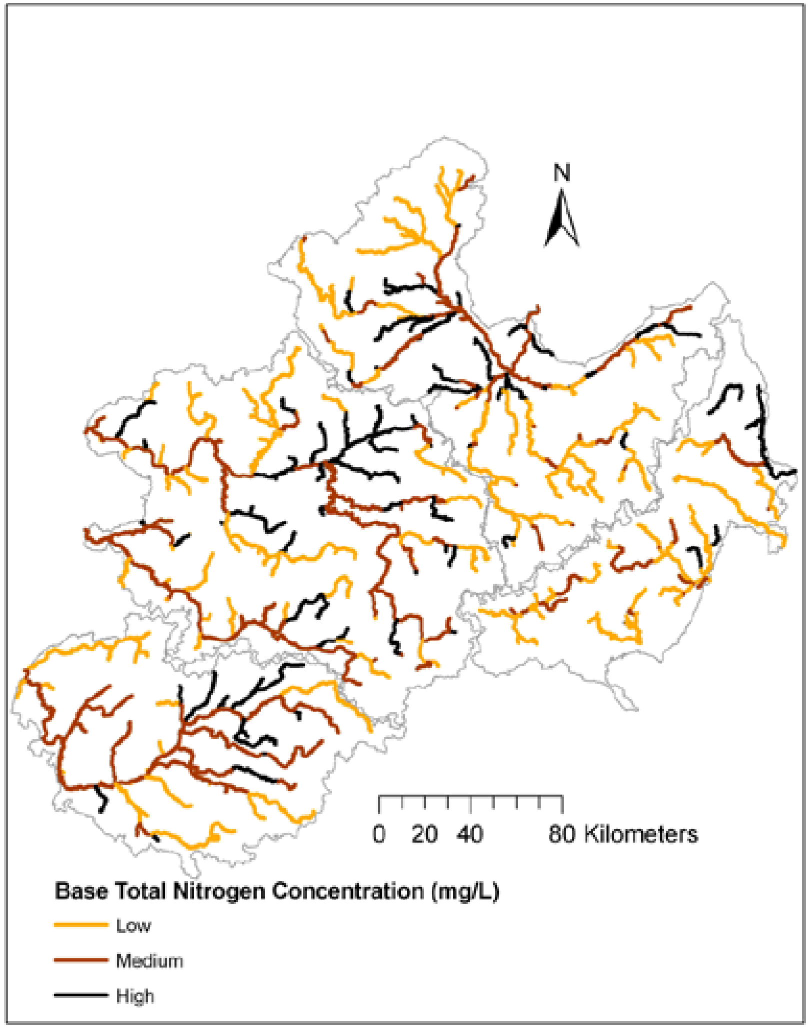
Low

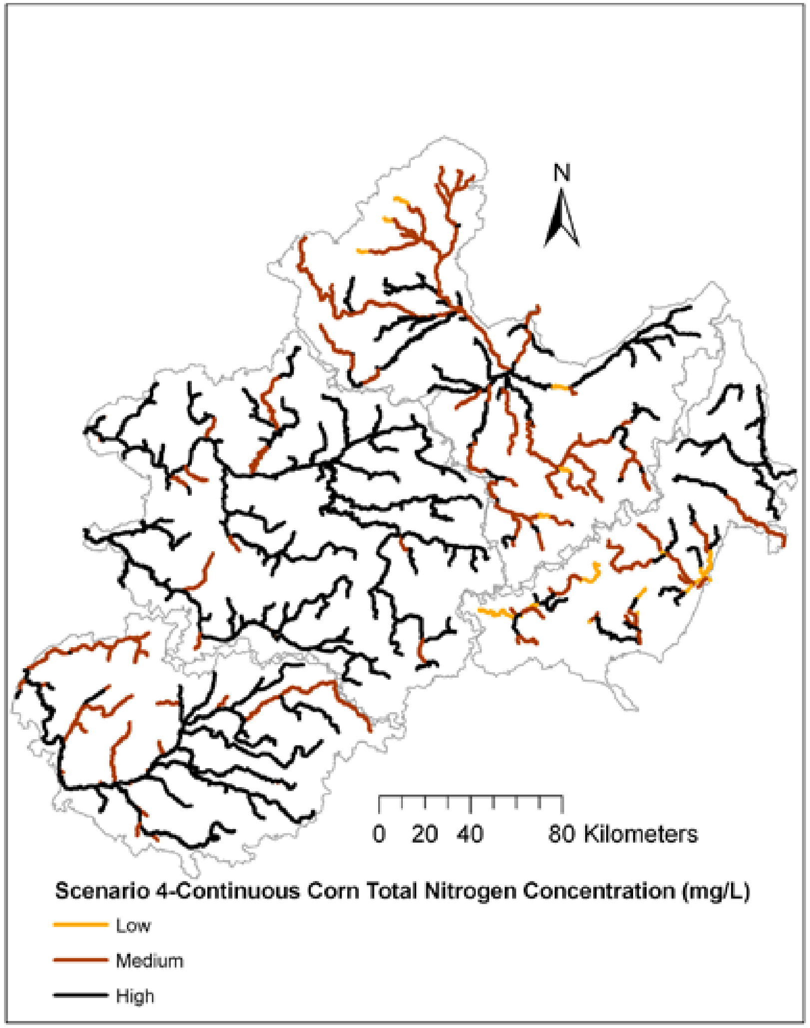
Medium

High

(Love, 2011)

Continuous Corn vs. Base (Nitrogen Concentration)



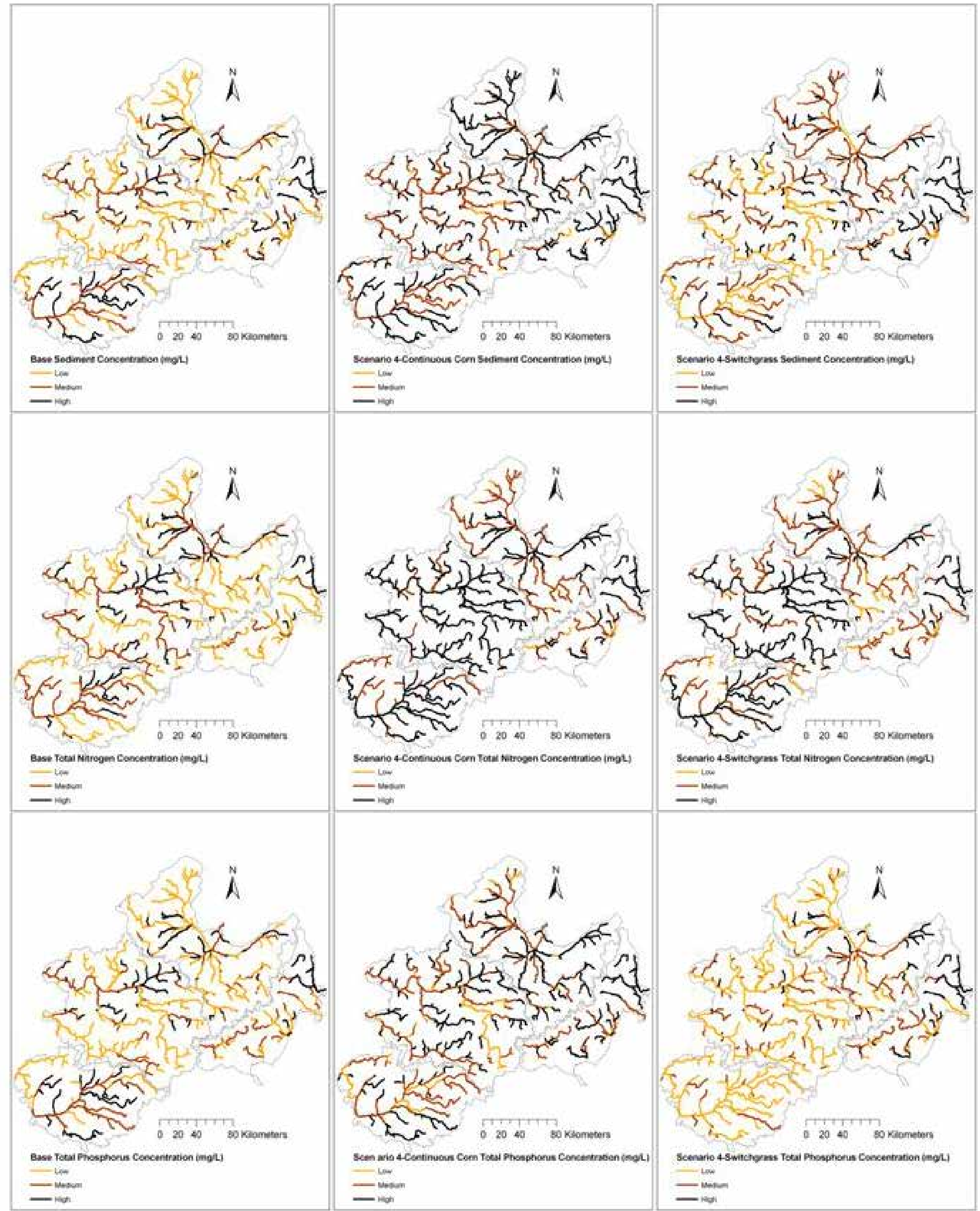


(Love, 2011)

Identifying Basin-wide Critical Areas for Aquatic Health

- Continuous Corn:
  - +40.83% in sediment load
  - + 38.88% in total nitrogen load
  - + 30.48% in total phosphorus load

- Switchgrass:
  - + 1.98% in sediment load
  - + 34% in total nitrogen
  - -12.12% in total phosphorus load



(Love, 2011)

Area of priority subbasins change from the Base Scenario (km^2)

	Sediment			Nitrogen			Phosphorus		
	Low	Medium	High	Low	Medium	High	Low	Medium	High
Continuous Canola	-16529	16375	154	-24645	22346	2299	-18995	20906	-1911
	-30.97	30.69	0.29	-46.18	41.87	4.31	-35.60	39.18	-3.58
Continuous Corn	-23877	21025	2852	-24371	21041	3330	-22485	22062	423
	-44.74	39.40	5.34	-45.67	39.43	6.24	-42.14	41.34	0.79
Continuous Corn stover	-18135	15976	2159	-29693	15821	13872	-24788	23815	974
	-33.98	29.94	4.05	-55.64	29.65	26.00	-46.45	44.63	1.82
Continuous Rye	-13255	14515	-1260	-14262	16986	-2724	4511	0	-4511
	-24.84	27.20	-2.36	-26.73	31.83	-5.10	8.45	0.00	-8.45
Continuous Sorghum	-22896	14455	8441	-22340	21553	787	-23627	21887	1741
	-42.91	27.09	15.82	-41.86	40.39	1.47	-44.28	41.01	3.26
Continuous Soybean	-21179	15560	5619	-27775	22371	5404	-23447	21657	1790
	-39.69	29.16	10.53	-52.05	41.92	10.13	-43.94	40.58	3.35
Corn Soy	-19561	15479	4082	-26973	23153	3820	-22577	21765	812
	-36.66	29.01	7.65	-50.55	43.39	7.16	-42.31	40.79	1.52
Corn Soy Rye	-15036	15780	-744	-22675	21616	1059	-9455	13014	-3559
	-28.18	29.57	-1.39	-42.49	40.51	1.98	-17.72	24.39	-6.67
Corn stover Soy	-19108	15571	3537	-28523	20169	8354	-23593	22120	1473
	-35.81	29.18	6.63	-53.45	37.80	15.65	-44.21	41.45	2.76
Sorghum Soy	-22257	14566	7691	-24734	23007	1727	-21842	21177	665
	22.21	-12.44	-9.78	-35.94	35.88	0.05	25.38	-16.93	-8.45
Miscanthus	11854	-6636	-5218	-19177	19149	28	13543	-9032	-4511
	20.86	-11.08	-9.78	-7.50	15.16	-7.66	29.19	-20.74	-8.45
Native Grass	11133	-5915	-5218	-4001	8089	-4088	15579	-11068	-4511
	-41.71	27.30	14.41	-46.35	43.11	3.24	-40.93	39.68	1.25
Switchgrass	-369	5121	-4752	-12866	15590	-2724	7672	-3161	-4511
	-0.69	9.60	-8.90	-24.11	29.21	-5.10	14.38	-5.92	-8.45

(Love, 2011)

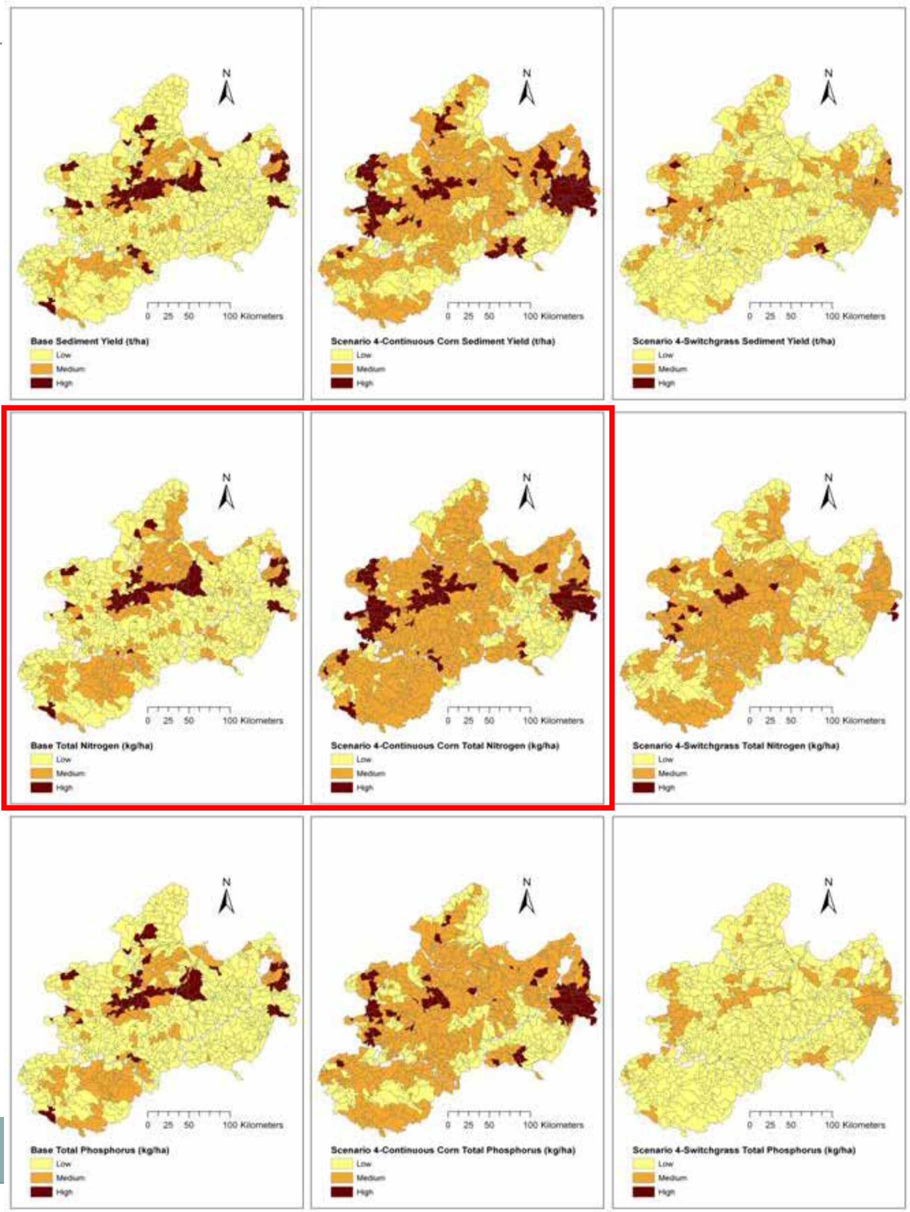
Priority Areas for Base, Continuous Corn, and Switchgrass Scenarios

Base | Corn | Switchgrass

Sediment

Nitrogen

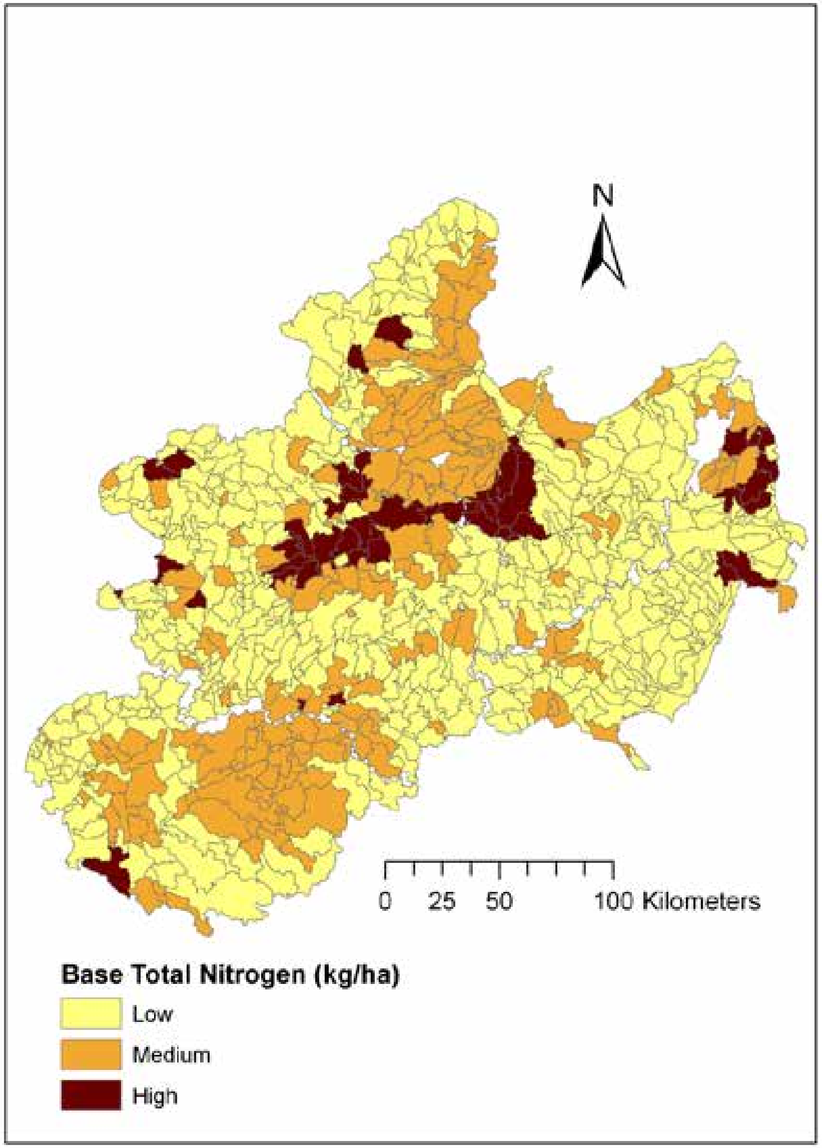
Phosphorus

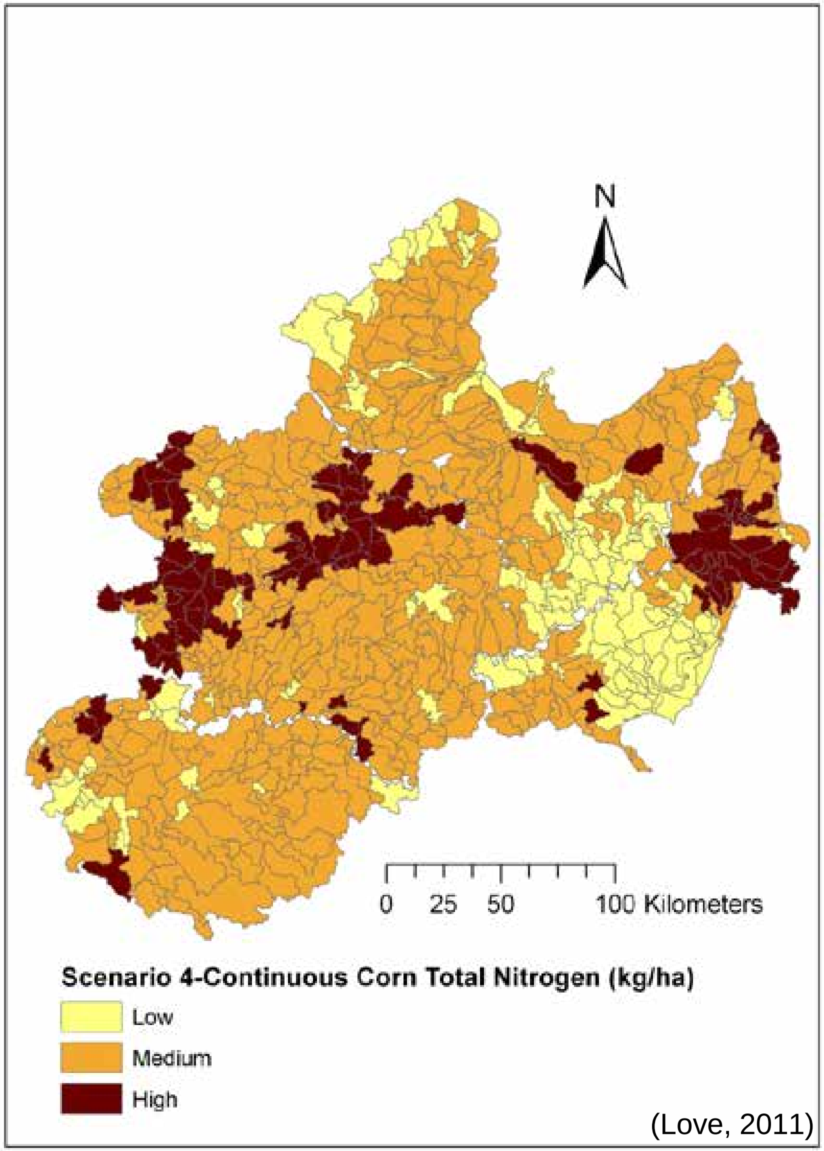


Low
Medium
High

(Love, 2011)

Continuous Corn vs. Base (Nitrogen Load)





(Love, 2011)

Basin-level Priority Areas for Targeting Conservation Efforts

– Continuous Corn:

+ 44.74% in sediment load

+ 45.67% in total nitrogen load

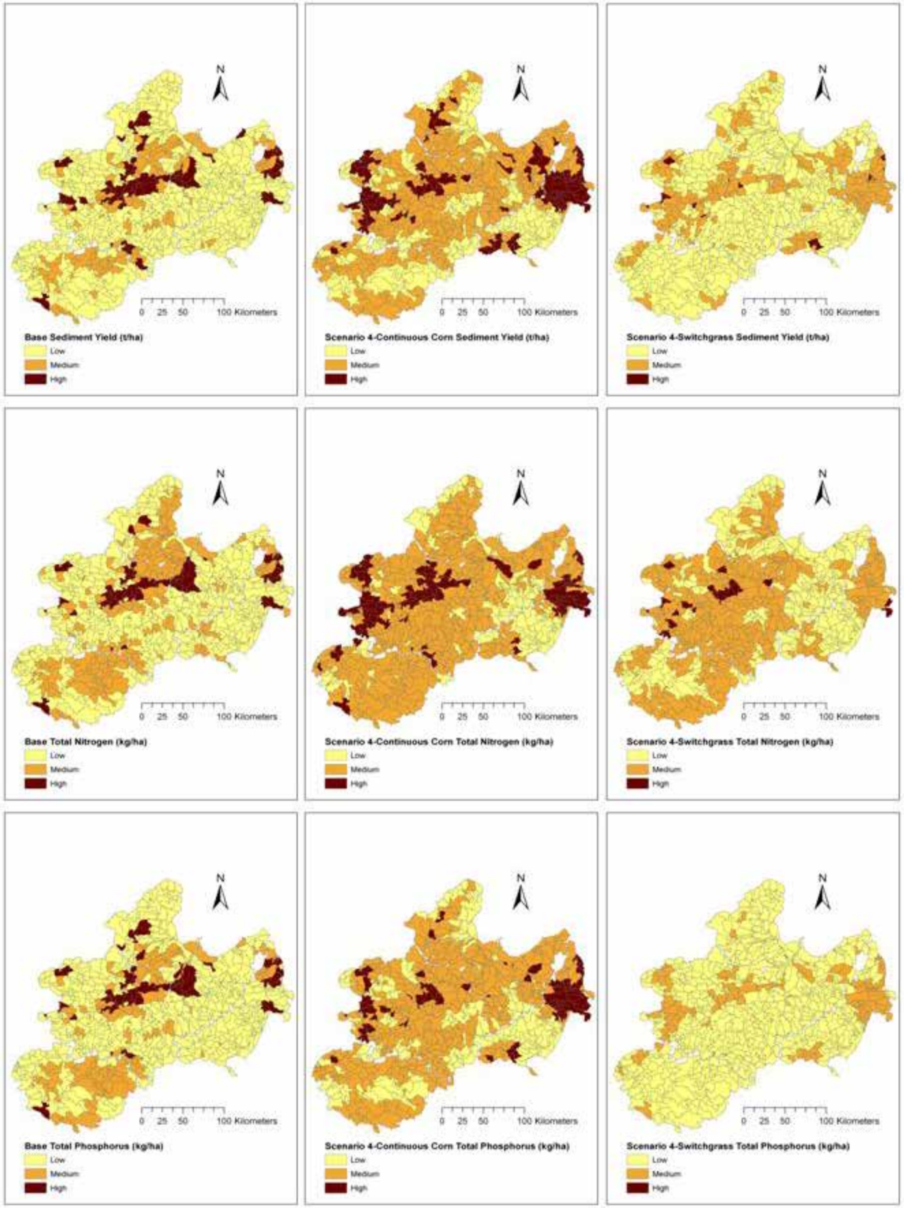
+ 42.13% in total phosphorus load

– Switchgrass:

- 8.9% in sediment load

- 5.1% in total nitrogen load

- 8.4% in total phosphorus load



(Love, 2011)

Summary Goal 2

- In general, the perennial grasses, although mixed benefits are present, are more suitable for implementation than intensive annual bioenergy crops.

Goal 3

- Suitability of bioenergy cropping rotations on different scenarios

  - Provide a comparison of all rotations based on their contribution to annual average sediment, nitrogen, and phosphorus loads for all landuse scenarios.

Total combined pollutant load of all watersheds

Sub-scenario	Sediment Load (tons)	Sediment % Change from Base	Total Nitrogen Load (kg)	Total Nitrogen % Change from Base	Total Phosphorus Load (kg)	Total Phosphorus % Change from Base
Base	473470	-	20062390	-	1606130	-
Scen1_Continuous Canola	474950	0.31	21992080	9.62	1212830	-24.49
Scen1_Continuous Corn	569040	20.19	21163620	5.49	1370890	-14.65
Scen1_Continuous CornStover	552470	16.69	27515330	37.15	1410920	-12.15
Scen1_Continuous Rye	399790	-15.56	17053860	-15.00	853790	-46.84
Scen1_Continuous Sorghum	662380	39.90	18350560	-8.53	1421670	-11.48
Scen1_Continuous Soybean	616680	30.25	22616070	12.73	1402420	-12.68
Scen1_Corn Soy	590170	24.65	21549760	7.41	1374450	-14.42
Scen1_Corn Soy Canola	597820	26.26	23932710	19.29	1460160	-9.09
Scen1_Corn Soy Rye	458230	-3.22	20540200	2.38	1070030	-33.38
Scen1_CornStover Soy	577190	21.91	23786210	18.56	1393350	-13.25
Scen1_Sorghum Soy	654390	38.21	19910470	-0.76	1345990	-16.20
Scen1_Miscanthus	91110	-80.76	20989570	4.62	802720	-50.02
Scen1_Native Grass	119280	-74.81	15993390	-20.28	677780	-57.80
Scen1_Switchgrass	282200	-40.40	17579150	-12.38	852380	-46.93
Scen4_Continuous Canola	649600	37.20	34461140	71.77	1674150	4.24
Scen4_Continuous Corn	772300	63.11	32483590	61.91	1963300	22.24
Scen4_Continuous CornStover	755900	59.65	44351540	121.07	2038100	26.90
Scen4_Continuous Rye	538090	13.65	25395310	26.58	1010140	-37.11
Scen4_Continuous Sorghum	887700	87.49	27805260	38.59	2047510	27.48
Scen4_Continuous Soybean	824700	74.18	35339620	76.15	2016760	25.57
Scen4_Corn Soy Rye	620860	31.13	31481110	56.92	1406110	-12.45
Scen4_Corn Soy	794200	67.74	33302840	66.00	1956950	21.84
Scen4_CornStover Soy	780300	64.80	37242850	85.64	2002750	24.69
Scen4_Sorghum Soy	872500	84.28	30532740	52.19	1896260	18.06
Scen4_Miscanthus	91850	-80.60	32404910	61.52	913240	-43.14
Scen4_Native Grass	135390	-71.40	23694470	18.10	679540	-57.69
Scen4_Switchgrass	366360	-22.62	26310980	31.15	994880	-38.06

(Love, 2011)

Continues Rye

Sediment		Total Nitrogen		Total Phosphorus	
Load (tons)	% Change from Base	Load (kg)	% Change from Base	Load (kg)	% Change from Base
Scenario 1					
399,790	-15.56	17,053,860	-15.00	853,790	-46.84
Scenario 2					
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Scenario 3					
629,560	32.97	36,226,820	80.57	1,382,460	-13.91
Scenario 4					
538,090	13.65	25,395,310	26.58	1.010.140	-37.11

Summary Goal 3

- Perennial grass species reduced sediment, nitrogen, and phosphorus loadings in Scenario 1 (Row Crops).
- It is not recommended to convert land under Scenarios 2 and 3 (Other Crops and Marginal Lands) to any bioenergy rotation in areas with preexisting high nitrogen levels.
- For Scenario 4 (All Agricultural Lands), the row crops make the condition worst while the perennial grass improve the water quality except for nitrogen.

Goal 4

- Statistical significance of bioenergy cropping rotations changes from base
  - The t-tests were performed to determine the statistical significance levels
  - *p*-value of 0.05 or less rejects the hypothesis that there is no significant differences in pollution generation between the bioenergy crop rotation and the current landuse scenario (Base Scenario).

Statistical Significance of Bioenergy Cropping Rotations Changes from Base

	p-value for given constituent		
	Sediment (tons)	Total N (kg)	Total P (kg)
Scen1_Continuous Canola	0.96590	0.00156	0.00009
Scen1_Continuous Corn	0.00000	0.02167	0.00000
Scen1_Continuous CornStover	0.00000	0.00000	0.00000
Scen1_Continuous Rye	0.09421	0.00029	0.00000
Scen1_Continuous Sorghum	0.00000	0.00318	0.00001
Scen1_Continuous Soybean	0.00000	0.00011	0.00000
Scen1_Corn Soy	0.00000	0.00286	0.00000
Scen1_Corn Soy Canola	0.00000	0.00000	0.00033
Scen1_Corn Soy Rye	0.66593	0.32899	0.00000
Scen1_CornStover Soy	0.00000	0.00000	0.00000
Scen1_Sorghum Soy	0.00000	0.00659	0.00000
Scen1_Miscanthus	0.00000	0.00000	0.00000
Scen1_Native Grass	0.00000	0.73903	0.00000
Scen1_Switchgrass	0.00024	0.00187	0.00000
Scen2_Continuous CornStover	0.00000	0.00000	0.00000
Scen2_CornStover Soy	0.00000	0.00000	0.00000
Scen2_Miscanthus	0.00000	0.00000	0.00000
Scen2_Native Grass	0.00000	0.00000	0.00000
Scen2_Switchgrass	0.00000	0.00000	0.00000
Scen3_Continuous Canola	0.00000	0.00000	0.65024
Scen3_Continuous Corn	0.00000	0.00000	0.05087
Scen3_Continuous Rye	0.00004	0.00000	0.00115
Scen3_Corn SoyCanola	0.00000	0.00000	0.01173
Scen3_Corn Soy Rye	0.00000	0.00000	0.04407
Scen3_Native Grass	0.80892	0.00000	0.00001
Scen3_Miscanthus	0.12460	0.00000	0.00001
Scen3_Switchgrass	0.00163	0.00000	0.00112
Scen4_Continuous Canola	0.00228	0.00000	0.60469
Scen4_Continuous Corn	0.00000	0.00000	0.00000
Scen4_Continuous CornStover	0.00000	0.00000	0.00000
Scen4_Continuous Rye	0.26324	0.00303	0.00007
Scen4_Continuous Sorghum	0.00000	0.00003	0.00000
Scen4_Continuous Soybean	0.00000	0.00000	0.00000
Scen4_Corn Soy Rye	0.00828	0.00000	0.08777
Scen4_Corn Soy	0.00000	0.00000	0.00000
Scen4_CornStover Soy	0.00000	0.00000	0.00000
Scen4_Sorghum Soy	0.00000	0.00000	0.00000
Scen4_Miscanthus	0.00000	0.02608	0.00000
Scen4_Native Grass	0.00000	0.00000	0.00000
Scen4_Switchgrass	0.07133	0.00171	0.00008

(Love, 2011)

Summary Goal 4

- In general perennial grass species significantly reduce sediment and phosphorus loads

- Bioenergy crops likely to increase nitrogen levels at all implementation scales

Overall Conclusions

- Perennial grass species are most suitable for large-scale implementation in this study area
- Traditional intensive row crops should be implemented with caution on such a broad scale
- Bioenergy row crops exhibit dramatic pollution load variation caused by differences in climate and physiographic characteristics throughout the study area

Relevent Publications

– Love B. J.. 2011. Environmental Impact Analysis of Biofuel Crops Expansion in Michigan. MS Thesis. Michigan State University

– Love B. J. and **A. P. Nejadhashemi**, 2011. Environmental Impact Analysis of Biofuel Crops Expansion in the Saginaw River Watershed. Journal of Biobased Materials and Bioenergy, 5(1): 30-54.

– Love, B. J. and **A. P. Nejadhashemi**, 2011, Water Quality Impact Assessment of Large Scale Biofuel Crops Expansion in Agricultural Regions of Michigan, Journal of Biomass & Bioenergy, 35(5): 2200-2216.

– Love, B. J., M. D. Einheuser and **A. P. Nejadhashemi**, 2011, Effects on Aquatic and Human Health due to Large Scale Bioenergy Crop Expansion, Science of the Total Environment, 409: 3215-3229.

– Einheuser, M., **A.P. Nejadhashemi**, S. A. Woznicki, 2013, Stream Health Sensitivity to Landscape Changes due to Bioenergy Crops Expansion. Biomass & Bioenergy, 58: 198-209.

Thank you!